# Ice Cloud Retrievals and Analysis with the Compact Scanning Submillimeter Imaging Radiometer and the Cloud Radar System during CRYSTAL FACE

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ABSTRACT

Submillimeter-wave radiometry is a new technique for determining ice water path (IWP) and particle size in upper-tropospheric ice clouds. The first brightness temperatures images of ice clouds above 340 GHz were measured by the Compact Scanning Submillimeter Imaging Radiometer (CoSSIR) during the Cirrus Regional Study of Tropical Anvils and Cirrus Layers (CRYSTAL) Florida Area Cirrus Experiment (FACE) campaign in July 2002. CoSSIR operated with 12 channels from receivers at 183, 220, 380, 487, and 640 GHz. CoSSIR and the nadir-viewing 94-GHz Cloud Radar System (CRS) flew on the NASA ER-2 airplane based out of Key West, Florida. A qualitative comparison of the CoSSIR brightness temperatures demonstrates that the submillimeter-wave frequencies are more sensitive to anvil ice cloud particles than are the lower frequencies. A Bayesian algorithm, with a priori microphysical information from in situ cloud probes, is used to retrieve the IWP and median mass equivalent sphere particle diameter ($D_{me}$). Microwave scattering properties of random aggregates of plates and aggregates of frozen droplets are computed with the discrete dipole approximation (DDA) and an effective medium approximation tuned to DDA results. As a test of the retrievals, the vertically integrated 94-GHz radar backscattering is also retrieved from the CoSSIR data and compared with that measured by the CRS. The integrated backscattering typically agrees within 1–2 dB for IWP from 1000 to 10 000 g m$^{-2}$, and while the disagreement increases for smaller IWP, it is typically within the Bayesian error bars. Retrievals made with only the three 183- and one 220-GHz channel are generally as good or better than those including 380 ± 6.2 and 640 GHz, because the CoSSIR submillimeter-wave channels were much noisier than expected. An algorithm to retrieve profiles of ice water content and $D_{me}$ from CRS and CoSSIR data was developed. This Bayesian algorithm also retrieves the coefficients of an IWC–radar reflectivity power-law relation and could be used to evaluate radar-only ice cloud retrieval algorithms.

## 1. Introduction

There are no methods for the accurate global remote sensing of ice cloud mass for climate studies (Wielicki et al. 1995). Global measurements of vertically integrated cloud ice mass [ice water path (IWP)] are important for evaluating climate model parameterizations and studying the upper-tropospheric water budget. Visible and infrared satellite remote sensing techniques for ice clouds (e.g., Rossow and Schiffer 1999; Stubenrauch et al. 1999) have poor accuracy for high IWP clouds, which contain much of the total cloud ice mass. Thermal infrared methods saturate with moderate optical depths and can only determine particle size (and, hence, IWP) for an effective radius below about 50 $\mu$m. Solar reflection methods cannot distinguish ice from underlying water cloud optical depth, cannot measure thinner clouds over bright surfaces, and can only retrieve particle sizes near the cloud top for optically thicker clouds, resulting in biased IWP retrievals. Millimeter-wave radar backscattering from CloudSat (Stephens et al. 2002), when combined with visible reflectance measurements, will improve the IWP retrieval accuracy; however, the radar's nadir view provides coverage that is too sparse to obtain a global climatology of the cloud ice mass with regional-scale resolution.

Theoretical studies (Gasiewski 1992; Evans and Stephens 1995b; Evans et al. 1998) have suggested that millimeter-wave and submillimeter-wave radiometry have the potential for accurate retrievals of cloud IWP and characteristic ice particle size. The technology of submillimeter-wave radiometry has lagged the theory, and only recently have the first submillimeter measurements of ice clouds been made from aircraft. The Far Infrared Sensor for Cirrus (FIRSC), which is a Fourier transform spectrometer with a cryogenic bolometer detector (Vanek et al. 2001), made measurements from 300 to above 1000 GHz during several campaigns. The sensitivity of FIRSC's bolometric detector precludes cross-track scanning, and the brightness temperature noise is high below about 800 GHz. The submillimeter-wave cloud –ice radiometer, developed at the Jet Propulsion Laboratory (Evans et al. 2002), has heterodyne receivers at 183, 325, 448, and 643 GHz, but has not yet been flown. The millimeter-wave imaging radiometer (MIR; Racette et al. 1996) had receivers at 89, 150, 183, and 220 GHz. Several groups have developed cloud IWP retrieval algorithms for MIR data at 89, 150, and

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TABLE 1. CoSSIR channel characteristics.

| Channel (GHz) | Center frequency (GHz) | Bandwidth (GHz) | System temperature (K) | NEΔT* (calculated) (K) | NEΔT** (measured) (K) |
|---|---|---|---|---|---|
| 183.3 ± 1.0 | 1.0 | 0.5 | 2500 | 0.55 | 0.90 |
| 183.3 ± 3.0 | 3.0 | 1.0 | 1390 | 0.23 | 0.61 |
| 183.3 ± 6.6 | 6.6 | 1.5 | 1050 | 0.15 | 0.75 |
| 220 | 2.5 | 3.0 | 1760 | 0.16 | 0.84 |
| 380.2 ± 0.8 | 0.75 | 0.7 | 3460 | 0.63 | NA |
| 380.2 ± 1.8 | 1.80 | 1.0 | 8440 | 1.23 | 4.01 |
| 380.2 ± 3.3 | 3.35 | 1.7 | 4820 | 0.55 | 4.25 |
| 380.2 ± 6.2 | 6.20 | 3.6 | 6670 | 0.52 | 4.99 |
| 487.25 ± 0.8 | 0.68 | 0.35 | 4650 | 1.17 | 2.57 |
| 487.25 ± 1.2 | 1.19 | 0.48 | 3890 | 0.85 | 1.66 |
| 487.25 ± 3.3 | 3.04 | 2.93 | 4600 | 0.40 | 2.05 |
| 640 | 2.5 | 3.0 | 16 000 | 1.33 | 4.90 |

* Calculated values based on the receiver system temperature measured in the laboratory and 50-ms integration time.
** Measured from the calibration target data on the 1 Jul flight with the same integration time.

220 GHz (Liu and Curry 2000; Deeter and Evans 2000; Weng and Grody 2000). A 340-GHz channel was later added to MIR, and significant brightness temperature depressions were observed from Arctic cirrus (Wang et al. 2001).

The Compact Scanning Submillimeter Imaging Radiometer (CoSSIR) is a new instrument with 15 channels from 183 to 640 GHz. CoSSIR flew for the first time on the National Aeronautics and Space Administration (NASA) ER-2 aircraft during the Cirrus Regional Study of Tropical Anvils and Cirrus Layers (CRYSTAL) Florida Area Cirrus Experiment (FACE) deployment out of Key West, Florida, in July 2002. One of the objectives of CRYSTAL FACE was the improvement and validation of remote sensing methods for near-tropical convective anvil ice clouds. The 94-GHz nadir-viewing Cloud Radar System (CRS) flew with CoSSIR on the ER-2. In this paper we describe CoSSIR and show examples of millimeter-wave and submillimeter-wave brightness temperature depressions that are associated with convective anvils in the south Florida region. We describe the retrieval of the ice water path and median volume equivalent sphere diameter ($D_{\mathrm{me}}$), using a Bayesian algorithm with updated prior information on ice cloud microphysics. The appendixes describe the in situ ice particle size distribution analysis and the particle shape modeling that are used in the prior distribution for the retrieval. Retrievals from CoSSIR of integrated radar reflectivity are compared with CRS data to evaluate the CoSSIR retrievals. Last, a new algorithm is presented to retrieve profiles of ice water content (IWC) and $D_{\mathrm{me}}$ from the combination of CoSSIR and CRS data.

## 6. Conclusions

The Compact Scanning Submillimeter Imaging Radiometer first flew in July 2002 during CRYSTAL FACE. Scanning across track, CoSSIR measured brightness temperatures in 12 channels with receivers at 183, 220, 380, 487, and 640 GHz. Although the submillimeter-wave channels were noisier than anticipated, the CoSSIR data demonstrate the high sensitivity of the submillimeter channels to ice cloud particles as compared with the lower frequencies. A Bayesian algorithm is used to retrieve the ice water path (IWP) and median volume equivalent sphere diameter ($D_{\mathrm{me}}$) from the available CoSSIR nadir brightness temperatures. Prior information that is used by the algorithm is obtained from radiosondes and in situ cloud microphysical probes on the Citation aircraft that was flown in CRYSTAL FACE. The retrievals are tested by retrieving vertically integrated 94-GHz radar backscattering from the CoSSIR data, which is then compared to Cloud Radar System (CRS) data. The integrated backscattering typically agrees to 1–2 dB for IWP from 1000 to 10 000 g m$^{-2}$, while for lower IWP the typical agreement is 3–5 dB, which is within the Bayesian error bars. Retrievals of integrated backscattering using only the 183- and 220-GHz CoSSIR channels have an agreement that is almost as good because of the high noise on the submillimeter channels.

An algorithm was developed to retrieve profiles of ice water content (IWC) and $D_{\mathrm{me}}$ from the combination of CRS reflectivity profiles and CoSSIR brightness temperatures. A power-law relation (IWC = $10^{0.1p} Z_e^q$) is assumed between IWC and equivalent radar reflectivity ($Z_e$), but the $p$ and $q$ coefficients are retrieved for each column. The IWC and $D_{\mathrm{me}}$ profiles and $p$ and $q$ are retrieved in a Bayesian integration that effectively matches the simulated and observed CoSSIR brightness temperatures. The radiometer data add additional information to the radar profile, so that the retrieved IWC and $D_{\mathrm{me}}$ are no longer completely dependent, as they are with a traditional IWC–$Z_e$ relation. The median retrieved $p$ and $q$ over all of the flights both increase from the a priori values for the highest IWP clouds. The results from the combined radar–radiometer profile algorithm illustrate how the coefficients for radar-only ice cloud retrieval methods could be tuned for particular cloud types using submillimeter radiometer data.

The CoSSIR-only retrievals of IWP and $D_{\mathrm{me}}$, and the combined CoSSIR and CRS retrievals of profiles of IWC and $D_{\mathrm{me}}$, are available in the CRYSTAL FACE archive (online at http://espoarchive.nasa.gov/). During CRYSTAL FACE the sensitivity of CoSSIR to lower IWP clouds was much poorer than anticipated because of the high noise of the submillimeter-wave channels. CoSSIR is currently being upgraded to improve the performance of the 380-, 487-, and 640-GHz receivers to noise equivalent temperatures of better than 1.0 K. The CoSSIR upgrade will also include the addition of a 874-GHz receiver for improved sensitivity to cirrus with smaller ice particle size.